Journal of Exercise Physiologyonline

December 2015
Volume 18 Number 6

JEPonline

Official Research Journal of the American Society of Exercise Physiologists

ISSN 1097-9751

Physiological Aspects of Walking in Simulated Hypogravity

Thomas Salisbury[1], Rafael Reimann Baptista[2], Joan Fei[2], Felipe Susin[2], Thais Russomano[2]

[1]Warwick Medical School, University of Warwick, Coventry, UK, [2]Microgravity Center, Pontifical Catholic University of Rio Grande do Sul, Brazil

ABSTRACT

Salisbury T, Baptista RR, Fei J, Susin F, Russomano T. Physiological Aspects of Walking in Simulated Hypogravity. **JEPonline** 2015;18(2):13-24. The purpose of this study was to compare the differences in gait between land (1G), Lunar (Lunar G), and Martian (Mars G) based ambulation. Nine subjects (mean age = 24.2 ± 3.4; weight = 69.88 ± 14.65kg; height = 163.22 ± 7.8cm; 5 male and 4 female) were placed in a Body Suspension Device (BSD) and had baseline oxygen consumption (VO_2) measured along with measures of comfort, pain, and exertion. Then, the BSD was engaged and the subjects underwent 10 min of walking at a self-selected speed in a simulated Mars G or Lunar G environment. The findings demonstrate that as gravity is decreased, self-selected walking speed decreases. However, there was no significant difference in relative and absolute VO_2 between Lunar G and Mars G. The experiment will be repeated using a lower body positive pressure device that will enable the comparison of results.

Key Words: Body weight support device, Weightlessness, Gate, Oxygen consumption.

INTRODUCTION

Gravity plays a central role in human locomotion. When walking in 1G humans have a distinguished walking gait in which one foot is always in contact with the ground. The gait cycle is divided into two main components: (a) the stance phase, where the limb is in contact with the ground; and (b) the swing phase, in which the foot is in the air for limb advancement. Walking can be compared to an inverted pendulum with the center of mass oscillating in a sinusoidal pattern. In forward walking, the center of mass is lowered during forward deceleration and raised during acceleration. This is so that kinetic energy and gravitational potential energy are continuously absorbed and restored by muscles and tendons (5).

Mechanical energy causes the center of mass to vault over the stance leg which is consequently converted into gravitational potential energy and a fraction of this is recovered by the pendulum mechanism of walking. However, human walking is far from an ideal pendulum. The ratio between kinetic energy and the gravitational potential energy needed during movement is described by the Froude number (Fr) with the greatest recovery of mechanical energy when Fr is equal to 0.25 (25).

Shortly before the first humans landed on the Moon in 1969, scientists speculated how the biomechanics of walking on its surface (which has a gravity of 1.622 m/s^2) would differ from the way humans walk on Earth (which has a gravitational field of 9.81 m/s^2). An early theoretical paper by Margaria and Cavagna (22) proposed that walking on the Moon would not be possible because little potential energy would be converted to kinetic energy and that jumping and running would be the only way to ambulate.

Astronauts on the Apollo missions later proved that walking on the Moon is feasible, although it was clear that the biomechanics of mobilizing in hypogravity differs significantly from terrestrial based movement. Since the initial research in the 60s and 70s, the topic has been mostly neglected by the scientific community. However, recent goals of increasing human presence in space, including a possible manned mission to Mars (4) and the construction of a Moon base (8,15), have revived interest in this area.

Understanding the biomechanics and energetics of walking in reduced gravity is not only relevant for space exploration, which includes spacesuit and habitat design as well as the refinement of life support systems for future Lunar and Martian planetary bases, it is also of significant importance for several patient populations on Earth (2,31). Ideally the best situation to study the biomechanics of walking is in an actual hypogravity environment. Unfortunately, technically it is impossible to truly reproduce hypogravity on Earth. The highest fidelity simulation of hypogravity is in a parabolic flight, in which volunteers experience temporary partial or full weightlessness depending on the profile of the parabola. However, the high cost coupled with the short duration of reduced gravity and the possibility of testing only a small number of volunteers limit the practicality of parabolic flight campaigns significantly for these investigations.

Other simulations include underwater treadmill, ballast systems (28), a partial body suspension system, and lower body positive pressure boxes (LBPP) boxes that are used to simulate hypogravity (34). In the latter technique, a combined pressure chamber-treadmill apparatus allows the individual to walk on a treadmill within a pressure chamber that comes up to the waist. This technique has many advantages: (a) individuals can move freely without experiencing the hydroviscosity of water; (b) the pressure within the chamber can be easily controlled to reproduce various levels of hypogravity; and (c) there is no need for training (7).

Simulating hypogravity using a body weight support or LBPP box has become a useful clinical tool for rehabilitation of individuals following traumatic injury, orthopedic surgery, and stroke. Reducing the physical load on patients who are too weak or who have difficulty in supporting their own body weight allows them to make stepping movements and, then, the load can be gradually increased as the patient improves. Indeed, walking under reduced loading may be more effective than traditional physiotherapy for rehabilitation because such “gait retraining” is accompanied by appropriate activation of sensory receptors at appropriate times in the gait cycle (3,7).

Body suspension devices (BSD) that use a modified harness to partially sustain the individual’s weight are an economical and practical alternative to other hypogravity simulation techniques. BSDs can be categorized into: (a) static systems; (b) active dynamic systems; (c) passive elastic systems; and (d) passive counterweight systems. The latter (used in the present experiment) utilizes counterweights (weight plates) in small increments to unload the individual’s body, which is suspended vertically in a work harness (20-21).

Few studies have examined the effect of Lunar and Martian gravity on the mechanics and the energetics of locomotion. Using the underwater treadmill and ballast technique, Newman and Alexander (28) showed that locomotion is altered in hypogravity. They reported that there was a linear decrease in stride frequency with lower gravity, although the slope of the reduction depended on walking speed the study looked at pre-set speeds of slow, medium or fast. They also showed that the expected decrease in VO_2 with decreasing gravity was non-linear. This result was thought to be a reflection of “wasted energy” used for posture and balance control in decreased gravity. In other studies that used different simulation techniques, similar results were found (5,14).

Understanding how healthy volunteers ambulate with BSD at self-selected, comfortable walking speeds is relevant for distinguishing the difference between healthy and pathological gaits when monitoring the progress of patients using BSD for rehabilitation (28). This is particularly illuminating for the reason quoted by Norman et al. (29) who believe that there are differences in gait patterns of normal volunteers when they are required to walk at speeds other than self-selected, comfortable walking speeds. Observations in patients with spinal cord injuries (SCI) and patients with knee related impairments indicate that self-selected walking speed in 1G is related to walking ability (1,3,27). Therefore, when lower limb movements and muscle activity patterns were studied during level and uphill walking in SCI patients, it was found that self-selected walking speed was the best indicator of SCI patient’s locomotor adaptation capacity (2). Barbeau (3) observed that SCI patients showed an increase in walking speed with BSD, which suggested an improvement in walking ability with this technique.

The purpose of this study was the compare the self-selected walking speed, VO_2, and perceived physical exertion of walking in simulated Lunar and Martian hypogravity with BSD in healthy male and female subjects.

METHODS

Subjects
Nine subjects (mean age = 24.2±3.4; weight = 69.88±14.65kg; height = 163.22±7.8cm; 5 men and 4 women) volunteered to participant in this study.

Procedures
A Body Suspension Device (BSD) was used to simulate hypogravity environments at ground level by decreasing the apparent weight of the suspended volunteer.

The BSD used in this study was designed and assembled at the Microgravity Center (MicroG) at PUCRS (21). It consisted of a steel frame, a suspension harness, and a counterweight system. The steel bars are 60 mm x 30 mm and the frame has a base of 300 cm x 226 cm with a height of 200 cm. The subjects were measured and weighed without the harness to calculate the counterweight as follows: Body mass (BM) and simulated gravity force (SGF), which was taken to be 1G for Earth, 3.71 m/s^2 for Mars G and 1,622 m/s^2 the Earth's gravity for Lunar G. This was then used to calculate relative mass (RM), as shown in Equation 1.

$$RM = (BM*SGF) \div 1G$$

The counterweight stack has nineteen 5 kg and one 7 kg weight, therefore, the maximum counterweight possible was 102 kg. Smaller weights (1 kg and 2 kg) were used to adjust the counterweight more precisely to each subject. To use this equipment, the subjects wore the device harness and, due to the BSD characteristics, they could not be taller than 175 cm. The harness is an adapted climbing harness attached to a pulley system. It was modified with pads in order to make it more comfortable for the subjects.

Each subject was tested at a controlled air-conditioned temperature that was pre-adjusted by the staff so the room was kept to 21° C. The subjects wore a T-shirt/top, shorts/skin-tight leggings, and trainers. A cardiotachometer (Polar S610, Electro Oy, Finland) was adjusted around the chest and VO_2 was measured with a mask that was placed over the subject's nose and mouth (VO2000, MedGraphics Corporations, St Paul, Minnesota, USA)

Once these procedures were concluded, the subject sat down and started the resting period to record the baseline heart rate and VO_2. The subject remained seated for 5 min while the data were collected and, then proceded to the treadmill to be attached to the BSD by one researcher while others adjusted the counterweights and prepared the computer.

First, the subject walked in the simulated Mars gravity for 10 min. During the first 3 min each subject individually adjusted the speed of the treadmill to the most comfortable setting. In the last 7 min, however, the speed was constant. During the 10-min walk, each subject was asked to answer to an adapted Borg Scale to indicate the Rate of Perceived Exertion (RPE), pain, and/or comfort that went from 1 to 10 (1 being none and 10 being maximum). The speed was measured using a tachometer. After the end of the walk, the subject's heart rate was allowed to return to baseline.

The counterweights were then adjusted to simulate the hypogravity environment of the Moon and all the data were collected again during a second 10-min walk to compare both situations of hypogravity. Then, the subject rested to return the heart rate to its baseline once again.

The final part of the test entailed the subject walking for 10 min in a 1G condition while wearing the device harness with all weights unloaded. For our analysis, the treadmill speed, the VO_2, RPE, pain, and comfort scales were recorded for comparison among the gravitational environments.

Statistical Analyses

Subsequent statistical analysis was performed with GraphPad InStat v3.00 for Windows. Repeated measure analysis of variance (ANOVA) and nonparametric tests were used (when the data were not normal) to compare the various measurements based on the level of gravity they were collected: VO_2, Velocity, RPE, Pain, and Comfort. To compare group means Tukeys was used as a post-test. The level of significance used was $P<0.05$.

RESULTS

The mean and individual velocities chosen by the subjects are shown in Figure 1. There was a statistically significant difference between the mean velocity chosen at 1G and Mars G (63.46 ± 19.62 $m \cdot min^{-1}$, 31.19 ± 10.84 $m \cdot min^{-1}$, $P<0.001$ respectively), as well as 1G and Lunar G (29.34 ± 9.79 $m \cdot min^{-1}$, $P<0.001$). However, when the velocities of Mars G and Lunar G were compared, no significant difference was found.

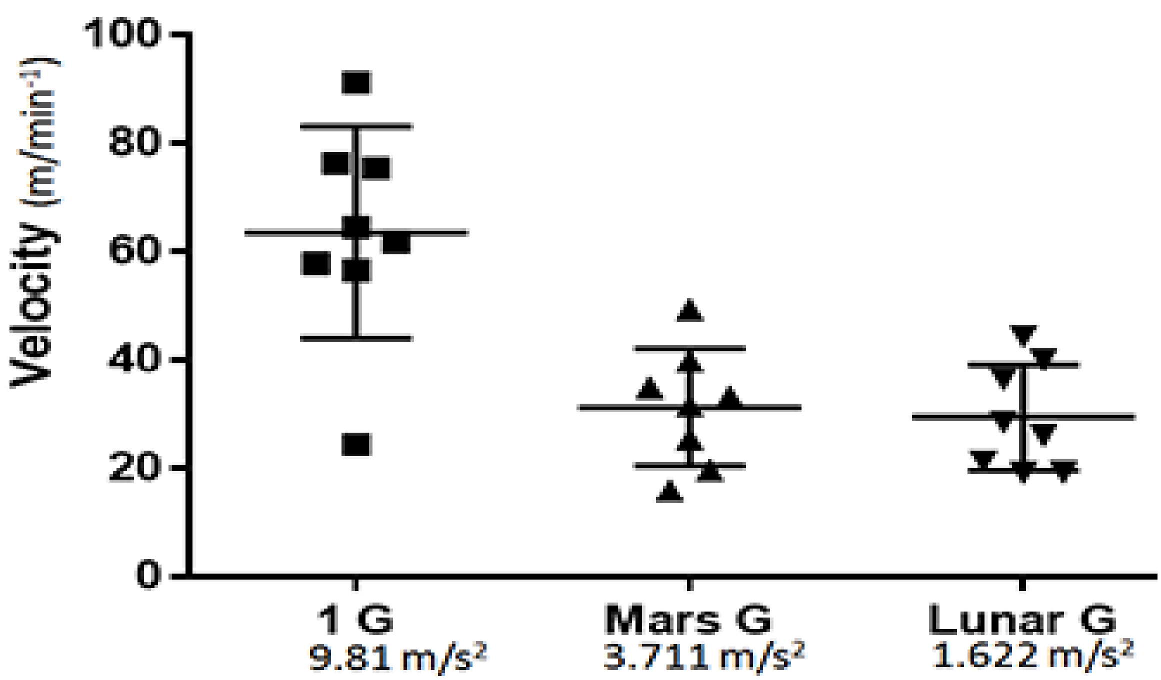

Figure 1. Walking Velocity Achieved by the Subjects at 1G (63.46 ± 19.62 $m \cdot min^{-1}$), **Mars G** (31.19 ± 10.84 $m \cdot min^{-1}$), **and Lunar G** (29.34 ± 9.79 $m \cdot min^{-1}$).

Mean VO_2 ($L \cdot min^{-1}$) and VO_2 relative to body mass ($mL \cdot kg^{-1} \cdot min^{-1}$) are summarized in Table 1. There was a statistically significant difference in both the absolute ($P<0.05$) and relative ($P<0.01$) VO_2 between rest and 1G. However, there were no significant differences found in VO_2 between the other groups.

Table 1. Mean Absolute and Relative Peak VO_2 Values.

	Groups			
	Rest	**1G**	**Mars G**	**Lunar G**
Peak VO_2 ($L \cdot min^{-1}$)	$0.28 \pm 0.05^{R\text{-}1G}$	0.55 ± 0.26	0.41 ± 0.14	0.39 ± 0.12
Peak VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	$3.99 \pm 0.67^{R\text{-}1G}$	8.13 ± 3.95	6.08 ± 2.63	5.74 ± 2.10

$^{R\text{-}1G}P<0.01$

The Borg scale findings are displayed in Figure 2. When comparing the results from the Borg CR10 Exertion Scale there were statistical variation between 1G *vs.* Lunar G ($P<0.05$). Yet, no statistical difference between any of the other groups was found. The Borg Pain Scale also showed statistically significant differences between 1G and Mars G ($P<0.05$) and between 1G and Lunar G ($P<0.01$). Despite this, no statistical differences were noted when comparing the Mars G and Lunar G results. Comfort scales yielded a noticeable difference in comfort levels between 1G and Mars G as well as 1G *vs.* Lunar G ($P<0.01$).

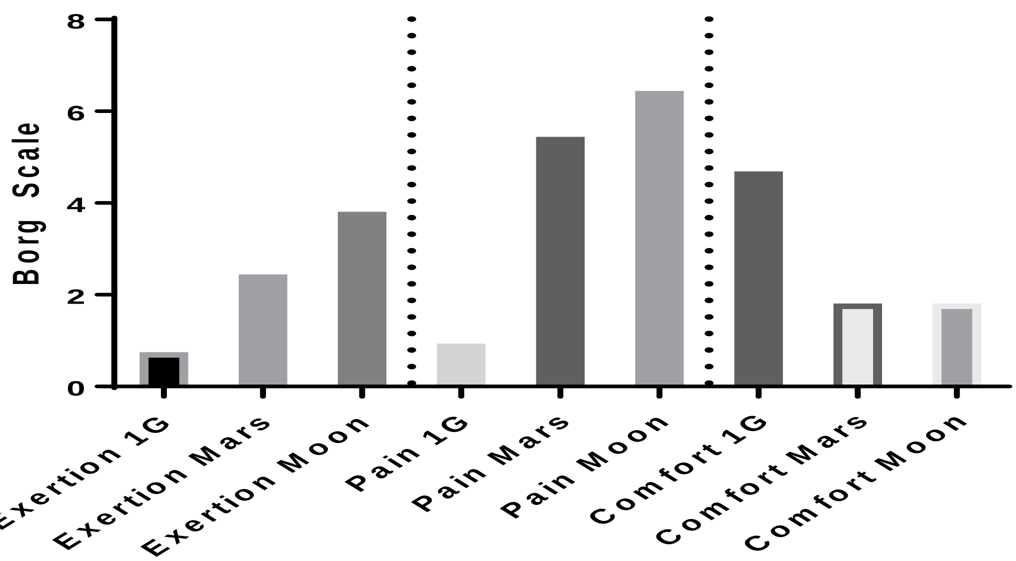

Figure 2. Borg Scale Reported by the Subjects for Exhaustion in 1G, Mars, and Moon (Lunar), respectively (0.69 ± 1.39, 2.38 ± 1.69, 3.75 ± 3.20), **Pain in 1G, Mars, and Moon (Lunar), respectively** (0.88 ± 2.47, 5.38 ± 2.77, 6.38 ± 2.33), **and Comfort Scores in 1G, Mars, and Moon (Lunar), respectively** (4.63 ± 0.74, 1.75 ± 0.46, 1.75 ± 0.71) (mean ± SD).

DISCUSSION

Our findings demonstrate that as gravity is reduced self-selected walking speed decreases. This decrease in exertion results in a lack of any statistically significant differences between the VO_2 responses in the three hypogravity groups. However, in this instance, the question is: Why do the subjects chose a lower walking speed in hypogravity when all previous studies indicate that hypogravity results in a reduction of energy expenditure? One explanation could be related to the preferred transition speed (PTS) from walking to running in hypogravity as the PTS is known to occur in progressively slower absolute speeds.

Equally important, the subjects were instructed to walk and not run plus the fact that running is known to be much more energy efficient in hypogravity resulted in an overall slower ambulation speed. The velocities chosen by subjects (assumed to be the optimal walking speed for them) varied vastly. However, the significant differences between 1G and both reduced gravity groups correlate with work previously done by Cavagna et al. (5), which showed that optimal speeds were lower at hypogravity. Kirsty et al. (20) allowed healthy subjects to choose their preferred walking speeds in simulated Martian gravity with a BSD and noted that chosen walking speeds reduced by just over 40% (n = 13).

As expected, the relative VO_2 and absolute VO_2 from rest to activity increased. However, there were no statistically significant differences among the three Gs (i.e., 1G, Mars G, and Lunar G). Other studies looking at VO_2 (9,11-12) have found that walking in a simulated hypogravity environment resulted in reduced metabolic expenditure. However, this may be due to some of these studies using different simulation methods of hypogravity. For example, Grabowski (12) noted that when using an LBPP to simulate hypogravity, the results differed compared to BWS devices. Perhaps, this is due to the horizontal and lateral support a LBPP provides over the purely vertical support from a BWS.

There are at least two explanations for our results not following the expected trends in hypogravity. First, our results may be due to a combination of the phenomena encountered by Grabowski (12) whereby decrease in net metabolic rate was not significant until gravity was <0.5G. Second our results may be due to a phenomenon noted by Farley et al. (9). They found that a reduction in gravity of 75% reduced energy consumption by 72% when running, yet when walking a gravity reduction of 75% only reduced energy consumption by 33%. The second explanation seems to be the better of the two for our results since the change in energy expenditure was not significant enough to be visible due to the subjects' self-selected walking speed, which masked any changes in the correlates of metabolic activity measured.

The results of Borg's CR10 exertion scale showed only one statistically significant subjective difference was reported between 1G and Lunar G. In this regard, two explanations should be considered. First, Lunar G requires the greatest deviation from normal gait patterns and, therefore, the most significant activation of various unused muscle groups. This fact would appear to explain the fatiguing adaptations within an abnormal gait cycle. Second, the generation of a Lunar G required the most vertical force applied from the BWS machine with considerable discomfort, which may have influenced the subjects' perceived exertion.

The statistically significant difference between 1G *vs.* Mars G and Lunar G Borg pain and comfort scores highlight several issues in the use of a BSD. The reported increase in pain may be due to gait cycle adaptations and the fatiguing of normally underused muscle groups. But, also, an important point is that the increased weight distributed to the harness and its associated straps when engaged caused increased discomfort as indicated on the pain scale.

This would explain why Mars G *vs.* Lunar G were both significant with a more noticeable difference between 1G and Lunar G as they both involved the BSD being engaged and taking body weight on the harness by varying amounts. Another plausible explanation may be that subjects confused the reporting of pain and exhaustion and allowed one to influence the other allowing some ambiguity to occur.

Data by Cavagna and colleagues (5) indicate that the proportion of internal work required to walk in hypogravity is increased compared to 1G. This may have an effect on the subjects' perception of physical exertion while walking in Martian gravity even though the absolute amount of internal work has not changed. More data on perceived physical exertion and VO_2 in healthy subjects walking at self-selected comfortable speeds in simulated hypogravity with BSD are needed to develop a reference for therapists using BSD for gait rehabilitation.

Due to the small number of male subjects in the present study, comparing the subjects by gender was not possible. But, it is already well-known that there are gender differences in the biomechanics of walking and running in 1G (6,16,18-19). Browning et al. (34) reported gender differences in the metabolic rate of walking. Specifically, they found that the net metabolic rate of walking in 1G is 10% greater in women than in men. However, it is still unknown whether gender differences in walking under conditions of hypogravity exist because of the very small number of female subjects involved in space physiology experiments.

Obviously, exploring gender differences in energy expenditure and mechanics of walking in hypogravity would fill an important gap in our knowledge of space physiology. It would also be relevant for future space suit design. The findings would be useful in the development of an appropriate reference for therapists who need to monitor the progress of male and female patients using BSD for gait rehabilitation.

Limitations of this particular technique include the: (a) discomfort of the harness; (b) lack of unloading above the torso; and (c) reduced freedom of movement, which may lead to reduction of movement in the extremes of hip flexion and extension (21,29). Although the latter is not an issue for patients who already have limited movement, this may affect the gait of healthy subjects. However, in spite of these limitations, BSD is a practical way to simulate hypogravity. Because it is a functional yet conservative use of space, it is useful for the rehabilitation of immediately post-operative patients without the risk of infection and can be easily used with patients and healthy individuals alike without any need for prior training.

However, it is interesting that there was no significant difference in velocity between Mars G and Lunar G (as would be expected by the reduced gravity). This may be explained by the inexperience of the subjects self-selecting a speed, or it may be due to the previously mentioned difficulties subjects experience with the harnesses (thus, introducing a form of equipment bias).

CONCLUSIONS

It was found that volunteers walked slower at Mars G and Lunar G compared to 1G, but there was not the progressive decrease in speed expected as G decreased. Additionally, perceived physical exertion did indeed increase in simulated hypogravity and there was no difference in VO_2 between Mars G and Lunar G.

These findings may have important implications to gait physiology in different gravitational environments such Martial and Lunar gravity. Since the next step in terms of space discovery is the return to the Moon as well as Mars exploration, our findings may contribute to a better understanding about the metabolic aspects of the astronaut's gait.

ACKNOWLEDGMENTS

We would like to thank the Pontifical Catholic University of Rio Grande do Sul for supporting this study.

Address for correspondence: Dr. Rafael Reimann Baptista, Microgravity Center, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil. 90619-900. Email: rafael.baptista@icloud.com

REFERENCES

1. Andriacchi TJ, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. ***J Biomech.*** 1977;10(4):261-268.

2. Barbeau H et al. Review: Walking after spinal cord injury: Control and recovery. ***The Neuroscientist.*** 1998;4(1):14-24.

3. Barbeau H, Wainberg M, Finch L. Description and application of a system for locomotor rehabilitation. ***Med Biol Eng Comput.*** 1987;25(3):341-344.

4. Browning RC, Baker EA, Herron JA, Kram R. Effects of obesity and sex on the energetic cost and preferred speed of walking. ***J Appl Physiol.*** 2006;100(2):390-398.

5. Cavagna G, Willems P, Heglund N. The role of gravity in human walking: Pendular energy exchange, external work and optimal speed. ***J Physiol.*** 2000;528(3):657-668.

6. Chumanov ES, Wall-Scheffler C, Heiderscheit BC. Gender differences in walking and running on level and inclined surfaces. ***Clin Biomech***. 2008;23(10):1260-1268.

7. Cutuk A et al. Ambulation in simulated fractional gravity using lower body positive pressure: Cardiovascular safety and gait analyses. ***J Appl Physiol.*** 2006;101(3):771-777.

8. Duke MB, Mendell WW, Roberts BB. Strategies for a permanent lunar base. In: ***Lunar Bases and Space Activities of the 21st Century,*** 1985.

9. Farle CT, McMahon TA. Energetics of walking and running: Insights from simulated reduced-gravity experiments. ***J Appl Physiol.*** 1992;73(6):2709-2712.

10. Folkow B, Gaskell P, Waaler B. Blood flow through limb muscles during heavy rhythmic exercise. ***Acta Physiol Scand.*** 1970;80(1):61-72.

11. Fox E et al. Oxygen cost during exercise in simulated subgravity environments. ***Aviat Space Environ Med.*** 1975;46(3):300-303.

12. Grabowski AM. Metabolic and biomechanical effects of velocity and weight support using a lower-body positive pressure device during walking. ***Arch Phys Med Rehab.*** 2010;91(6):951-957.

13. Grabowski A, Farley CT, Kram R. Independent metabolic costs of supporting body weight and accelerating body mass during walking. ***J Appl Physiol.*** 2005;98(2):579-583.

14. Griffin TM, Tolani NA, Kram R. Walking in simulated reduced gravity: Mechanical energy fluctuations and exchange. ***J Appl Physiol***. 1999;86(1):383-390.

15. Happel JA. Indigenous materials for lunar construction. ***Appl Mech Rev.*** 1993;46(6): 313-325.

16. Hirokawa S. Normal gait characteristics under temporal and distance constraints. ***J Biomed Eng***. 1989;11(6):449-456.

17. Holmgren A. Circulatory changes during muscular work in man; with special reference to arterial and central venous pressures in the systemic circulation. ***Scand J Clin Lab Invest.*** 1956;8:1.

18. Hurd WJ et al. Differences in normal and perturbed walking kinematics between male and female athletes. ***Clin Biomech.*** 2004;19(5):465-472.

19. Kerrigan DC, Todd MK, Croce UD. Gender differences in joint biomechanics during walking normative study in young adults. ***Am J Phys Med Rehab.*** 1998;77(1):2-7.

20. Kirsty L. A comparison of walking gait on Earth and in Mars simulated gravity. ***Space Physiol Health.*** 2013, Kings College London, UK.

21. Leães R et al. Development of walking pattern evaluation system for hypogravity simulation. In: ***Engineering in Medicine and Biology Society.*** 2006. EMBS'06. 28th Annual International Conference of the IEEE. 2006. IEEE.

22. Margaria R, Cavagna G. Human locomotion in subgravity. ***Aerospace Med***. 1964;35: 1140-1146.

23. MarsOneTeam. Mars One. 2013; Available at: http://www.mars-one.com/

24. Mayerson H, Burch G. Relationships of tissue (subcutaneous and intramuscular) and venous pressures to syncope induced in man by gravity. ***Am J Physiol***. 1939;128 (2):258-269.

25. Minetti AE. Biomechanics: Walking on other planets. ***Nature,*** 2001;409(6819):467-469.

26. Möltner A, Hölzl R, Strian F. Heart rate changes as an autonomic component of the pain response. ***Pain.*** 1990;43(1):81-89.

27. Moseley AM et al. Treadmill training and body weight support for walking after stroke. ***Cochrane Database Syst Rev.*** 2005;4.

28. Newman DJ, Alexander HL. Human locomotion and workload for simulated lunar and Martian environments. ***Acta Astronautica.*** 1993;29(8):613-620.

29. Norman KE et al. A treadmill apparatus and harness support for evaluation and rehabilitation of gait. ***Arch Phys Med Rehab.*** 1995;76(8):772-778.

30. Smit AA et al. Pathophysiological basis of orthostatic hypotension in autonomic failure. ***J Physiol.*** 1999;519(1):1-10.

31. Tenforde AS et al. Use of an antigravity treadmill for rehabilitation of a pelvic stress injury. ***PM&R.*** 2012;4(8):629-631.

32. Wang Y, Marshall RJ, Shepherd JT. The effect of changes in posture and of graded exercise on stroke volume in man. ***J Clin Invest.*** 1960;39(7):1051.

33. Wieling W, Krediet CTP, Tschakovsky ME, Dijk NV. Initial orthostatic hypotension: Review of a forgotten condition. ***Clin Sci.*** 2007;112:157-165.

34. Zhang WX, Zhan CL, Geng XC, Mu DW, Lu X, Yan GD, Chu X. Decreased +gz tolerance following lower body positive pressure: Simulated push-pull effect. ***Aviat Space Environ Med.*** 2001;72(11):1045-1047.